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# Low Noise Optical Link Development at INRIM

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## ABSTRACT

At the beginning of 2009 INRIM, the Italian metrological laboratory, started a research activity in order to realize a low noise optical link. Two telecom fiber lasers at 1550nm have been locked on two independent notched ultralow expansion glass (ULE) Fabry-Pérot cavities. We present the thermal stabilization system, and report the finite-element analysis (FEA) made to precisely determinate the positions of the cavity supports.

The sensitivity of optical axes length to acceleration is found to be less than 4.5 pm/g . Two different commercial lasers are stabilized by a Pound-Drever-Hall (PDH) technique and a stability of  $6 \times 10^{-14}$  is achieved at 1 s. Finally, the experimental set-up for the optical link is described and a first noise cancellation result on a 25 km long fiber is reported.

## INTRODUCTION

In the last decade, remote atomic frequency standards comparisons have been accomplished by various techniques mainly based on satellite links, with an instability slightly below  $1 \times 10^{-14}$  after one day of integration time [1]. These comparison methods are not stable enough to withstand the noise and stability level of the better optical clocks, whose stability has been demonstrated to be in the  $10^{-15}$  range at 1 s, and their accuracy is pushing toward the  $10^{-18}$  range.

In recent years a new frequency comparison method, based on the transfer of an optical carrier in telecommunication fiber, was successfully demonstrated, for fiber path over than hundred kilometers [2]: this method, based on phase noise compensation, is able to reach a noise floor of the order of  $10^{-19}$  at 10 000 s opening the feasibility of a continental scale comparisons by fiber links [3]-[6].

Here we show the set-up for the optical link and we describe the firsts results obtained. The laser natural linewidth was measured to be between 10 and 20 kHz, not enough for the link requirements, where the optical delay of the two way path can be as large as 1ms. It is hence mandatory to stabilize the laser onto an external high finesse cavity, in order to reduce its linewidth and to improve its stability. To this purpose two independent high finesse cavity were used, one for each laser. The cavities are realized in ULE, and are notched according to a design originally developed by Till Rosenband of NIST. This design allows to realize a simple anti-vibration support, where the mechanical deformation of the cavity optical axes length are first order compensated by the non uniform cavity mass distribution.

## ANALYSIS OF MECHANICAL VIBRATIONS

We have performed a Finite Element Analysis (FEA) to investigate the elastic deformation of the Fabry-Pérot cavity when supported by four rubber pads [7, 8]. Any vibration (i.e. variation in the gravitational acceleration  $g$ ) alter the distance between the cavity mirrors, however if the cavity is supported on four specific points, known as Airy points, the optical length of the cavity doesn't change. The purpose of the simulation is to determine the position of these points and the correct size of the pads used to support the cavity. To perform the FEA we analyzed the structure with a commercial software [9].

Fig. 1 shows the result of the deformation along a plane passing through the optical axis, when the cavity is leaned on four pads. This deformation takes into account the elongation suffered by the cavity when a vertical acceleration  $g$  is applied. While the mirrors are represented with the same color, areas above the pads have

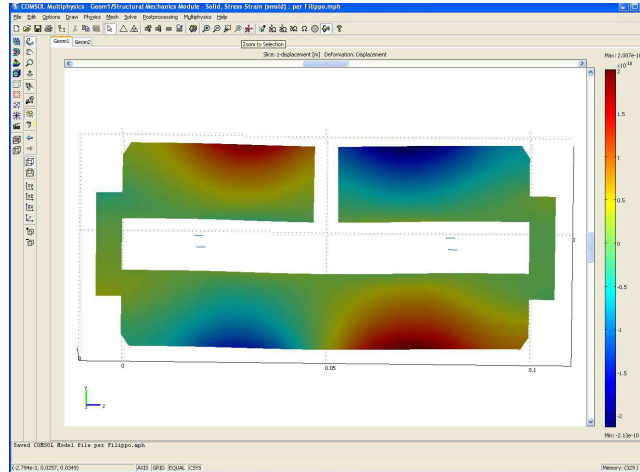


Fig. 1: Deformation of the cavity along the vertical plane passing through the optical axis.

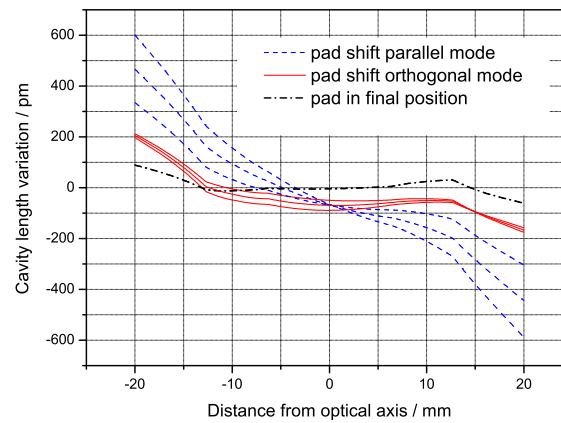


Fig. 2: Variation in the cavity length when pads are shifted parallel (dashed blue lines) and perpendicular (continuous red lines) to the optical axis; minimum variation of the cavity length (dot-dashed black line).

a different color than other parts of the cavity. In particular, the straining is significantly different near the support points and in the nearby areas, where the structure stress is higher. To find the correct position, we moved the pad coordinates until we minimize the variations in the length of the optical axis. To reduce the computation time, and taking advantage of the cavity symmetry, only a quarter of cavity was considered.

Fig. 2 shows how the distance between the mirror ( $z$  – displacement) and the vertical plane passing in the center of the cavity varies with the pad in different positions and when a vertical acceleration  $g$  is applied. The horizontal axis represents the distance from the optical axis, while the vertical one is the cavity length variation. Each curve is obtained with the pad in a well defined position. Dashed lines are obtained shifting the pads parallel to the optical axis, from 16 mm to 18 mm from the mirror and at 5 mm from the internal surface of the ULE spacer: the figure shows that mirrors rotate around their center. We have chosen to use square pads  $2 \times 2 \text{ mm}^2$ . The cavity length variations are shown with continuous lines: by moving the pads from 6 mm to 4 mm from the the internal surface of the ULE spacer, the distance between the mirrors changes but, as can be seen in Fig. 2 they maintain themselves almost in parallel position. Finally we found the location of pads that minimizes deflection in the mirrors: pads are placed at 1.9 cm from them and at 2 mm from the internal surface of the ULE spacer. ULE length variation is showed in Fig. 2 with dot-dashed line and in Fig. 3. The analysis carried out shows that, in this position, the gravitational force changes the distance between the mirrors less than 4.5  $\mu\text{m}$ .

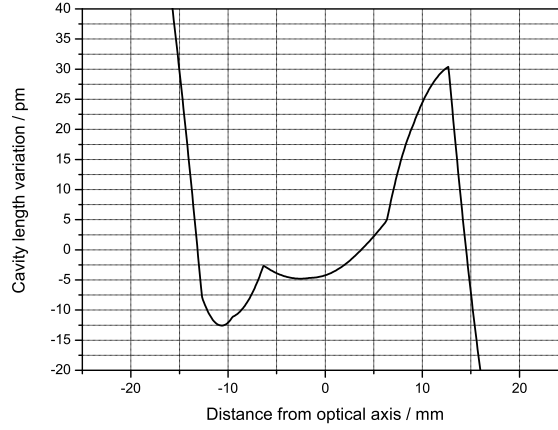


Fig. 3: Variation in the cavity length when the pad is placed at 1.9 cm from the mirror and at 2 mm from the *ULE* spacer.

## OPTICAL CAVITY THERMAL STABILIZATION

If mechanical vibration can results in a broader linewidth of the laser locked on the reference cavity, the temperature variation produce a long term frequency drift. Even if it is not strictly required to reduce the long term drift of the reference cavity for the realization of the optical link, nonetheless it is useful for several characterization to have the cavity temperature under control. To realize a good passive temperature filter we have realized a thermal insulation system: the cavity is housed in a copper thermal shield inside a vacuum chamber (residual pressure of  $6 \times 10^{-6}$  Pa is obtained), used to isolate the cavity from the thermal radiation. The copper shield is hold in its position with ceramic and nylon screws in order to reduce its thermal conductivity with the external world. The cavity is leaned on an aluminum support through four VITON pads (cross sectional area equal to  $2 \times 2$  mm<sup>2</sup>).

Four ceramic screws are placed like spacers to avoid conductive heat transfer between the shield and vacuum chamber. In this manner the cavity is extremely well insulated from the laboratory temperature fluctuation. The thermal time constant of the cavity was measured to be  $> 5000$  s. In this condition it is enough to stabilize the temperature by few mK on the long term to attain a short term temperature stability well below 1  $\mu$ K. A temperature of 305 K is set by a proportional integral derivative (PID) controller driving a heater covering the external side of the vacuum chamber. The temperature measurement is obtained by a Negative Temperature Coefficient (NTC) resistor placed on the copper shield. Since it is not recommended to place a thermistor at direct contact of the cavity, test were done with a block of glass of roughly the same mass of the cavity. With this experiment we could figure out that a much better measurement of the cavity temperature could be done if the temperature servo thermistor is placed onto a small piece of glass below the cavity body. The graph here reported (Fig.4) shows the Allan deviation of the temperature acquired by a 34410A Agilent multimeter connected to NTC placed on the test point. Up to 10 s the stability measurement is limited by the measurement noise, while the stability at 1 s must be extrapolated from the graph, assuming a linear trend for more than 40 s: an Allan deviation of 0.2  $\mu$ K at 1 s is achieved. This stability should be enough to keep the thermal drift of the cavity below  $10^{-15}$  Hz/s.

## POUND DREVER HALL LASER FREQUENCY STABILIZATION

Pound-Drever-Hall [10] technique is used to stabilize two lasers at 1542 nm by means of two independent Fabry-Pérot cavities. The laser frequency is corrected with a fiber coupled Acoustic Optic Modulator (AOM) and by a piezoelectric actuator directly in the laser head: a resonant electro-optic-modulator (EOM) is used to modulate the phase of the optical carrier (see Fig.5).

The AOM is driven at 40 MHz, while a RF of 7 MHz is sent to EOM and to the mixer input. The Pound-Drever-Hall signal is obtained from the mixer output. The cavity reflected beam is focused on a photodiode (PD) to obtain the error signal used to control the laser frequency. Piezoelectric driver and voltage-controlled

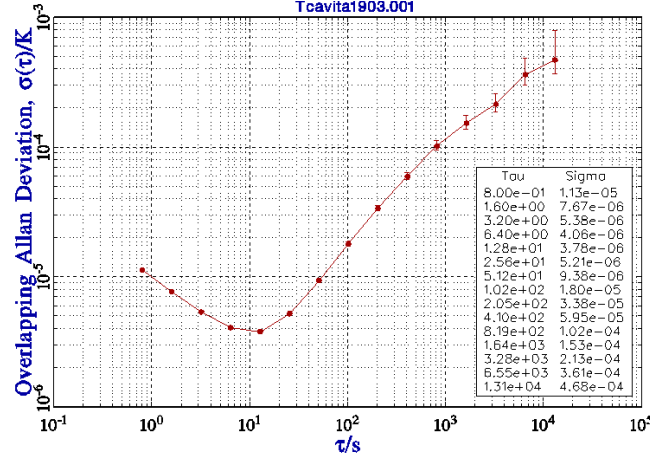


Fig. 4: Temperature stability of the block of glass of roughly the same mass of the cavity.

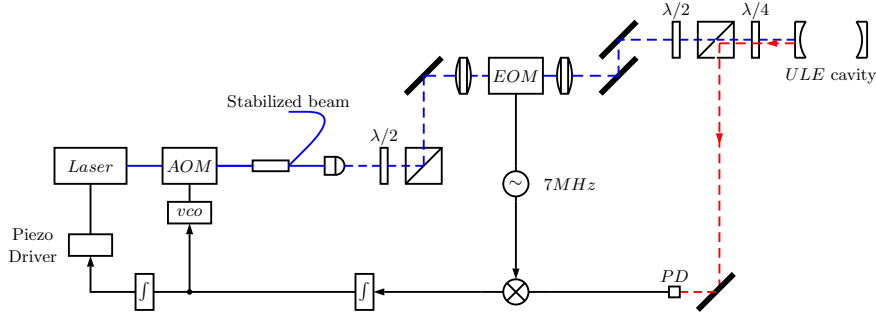


Fig. 5: Locking the laser to the cavity: optoelectronic set-up.

oscillator (vco) correct slow and fast frequency changes respectively. The stability of the two laser locked with PDH technique to the respective cavities was measured by a beat notes, its Allan deviation is showed in Fig.6 and gives a stability of  $6 \times 10^{-14}$  at 1 s. In the near future, we plan to reduce the long term drift by implementing the above mentioned temperature control. Also an improvement of the PDH bandwidth is planned for short term stability improvement.

## COHERENT OPTICAL PHASE TRANSFER

Once performed the laser stabilization we realized a preliminary experimental set-up for a 25km fiber link in the laboratory. As depicted in fig.7 the stabilized laser is sent into the fiber, and at the end of the path it is amplified and back reflected. A power splitter extracts a fraction of the laser that is beaten with the input laser and is used as monitor signal. The stabilized laser is beaten with itself after a round-trip through a 25 km optical fiber circuit on a photodiode. The signal obtained is used to control, by means of an AOM, the laser frequency and to compensate the phase noise introduced by the fiber. A second AOM is put at the end of the fiber, and is used to shift the laser frequency to discriminate between unwanted reflections. In the present set-up we are also using an optical amplifier to regenerate the laser power before the retro-reflection at the fiber end. Once the control is activated, the beat note between the input stabilized laser and the laser delivered at the final user is acquired with a spectrum analyzer. Fig.8 and fig.9 show the reduction of the beat note noise in the open and closed loop conditions and the Allan deviation for the round-trip optical link.

The measurement of the frequency stability of this beat note in the closed loop condition shows a short term stability of  $1 \times 10^{-15}$  at 1 s and a stability around  $3 \times 10^{-17}$  at  $10^4$  second.

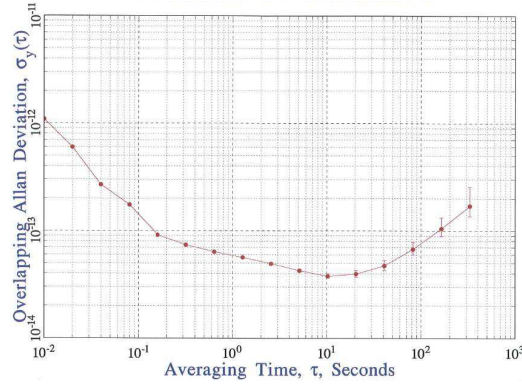


Fig. 6: Stability of the two stabilized fiber lasers locked on the two independent ULE cavities without temperature control system.

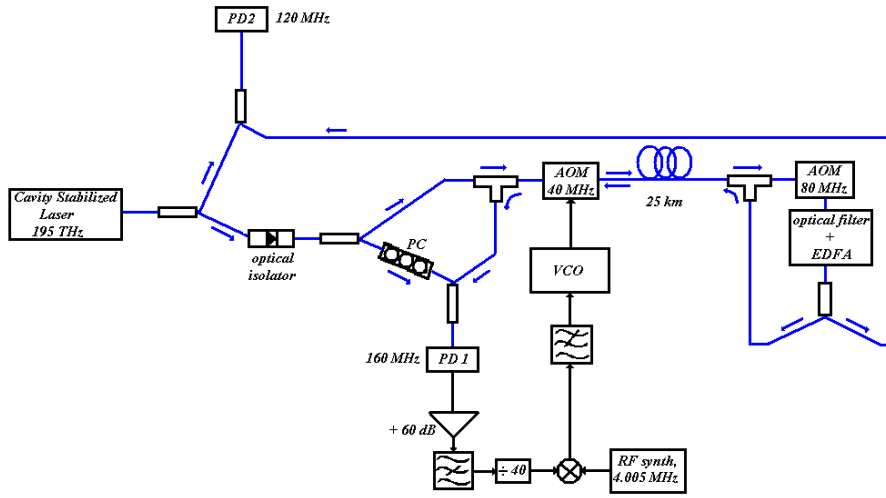


Fig. 7: Experimental setup for the frequency transfer and fiber stabilization

## CONCLUSIONS

We have reported the work made to realized a coherent transport of a laser carrier over a 25 km long fiber optic link with phase noise suppression. Firstly, we have obtained a cavity thermal stability of  $0.2 \mu\text{K}$  at 1 s, then we have described the FEA analysis made to plan the correct supports for the cavity that can minimize its sensitivity to vertical acceleration. Following this we have stabilized two independent lasers on two different ULE Fabry-Pérot cavities obtaining a laser stability of  $6 \times 10^{-14}$  at 1 second. Finally we have performed a first optical link experiment obtaining the reduction of the phase noise introduced in a 25 km fiber optic spoil.

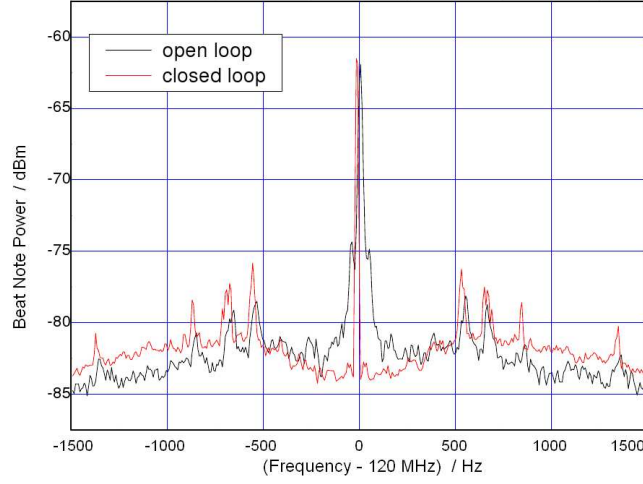


Fig. 8: Power spectra of the beat notes (PD2) versus Fourier frequency for the round-trip optical link with (red curve) and without (black curve) control of the noise around the optical carrier (RBW= 10 Hz)

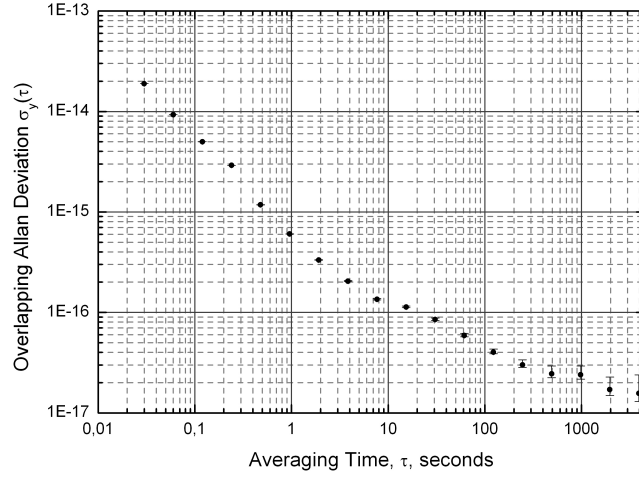


Fig. 9: Allan deviation for the round-trip optical link.

## ACKNOWLEDGMENTS

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